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Research on Sustainable Offshore Energy Development in the Context of Carbon Neutrality and Carbon Peaking, Combined with CCUS

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Abstract

In the context of the new era of "dual-carbon" economy, an increasing number of industries are moving towards low-carbon economic development. Low-carbon development strategies and efficient resource utilization have gradually become indispensable conditions and foundations for sustainable development in various sectors. China's energy structure is rapidly transitioning towards diversification, clean energy, and low-carbon solutions. To more effectively explore, develop, and utilize various offshore energy resources, this paper proposes an integrated offshore energy development model combined with CCUS (Carbon Capture, Utilization, and Storage) technology, aiming to achieve sustainable development of offshore energy. Firstly, electricity is generated through offshore wind power, photovoltaic systems, tidal energy, and salinity gradient power, providing a continuous supply of clean energy to offshore oil platforms and marine ranches, thereby achieving efficient energy utilization. Secondly, waste gases produced during operations are managed through CCUS technology to achieve low-carbon or even zero-carbon emissions, enabling zero-carbon offshore production and living. Furthermore, the integrated construction model of new energy and CCUS facilitates the efficient utilization of carbon dioxide. Ultimately, this study provides strategic recommendations for the sustainable development of offshore energy, including the use of electricity, fossil fuels, nuclear energy, hydrogen, and other clean and efficient energy sources, thereby advancing research on the sustainable development of integrated offshore energy systems.

Keywords

Offshore energy; Carbon peak; Carbon neutrality; Low-carbon; Sustainable development

1. Introduction

1.1 Research Background

China, with its abundant marine resources, has been emphasizing the development of a marine economy and the protection of marine ecological environments. As

President Xi Jinping highlighted in his report at the 20th National Congress of the Communist Party of China, building a strong marine nation is crucial for advancing Chinese modernization. In the 14th Five-Year Plan period, China has been committed to achieving the "dual-carbon" goals and constructing a modern power system dominated by new energy. [1]China has made remarkable progress in solar and wind energy, with renewable energy generation capacity growing by 18.2% year-on-year. However, the integration of different marine energy systems still faces challenges such as lack of coordination and immature integration technologies.

Carbon Capture, Utilization and Storage (CCUS) technology plays a vital role in controlling and converting carbon emissions. On August 2, 2024, the General Office of the State Council issued the "Work Plan for Accelerating the Construction of a Carbon Emission Double Control System." During the 15th Five-Year Plan period, carbon emission intensity will be a binding indicator, and carbon emission total accounting work will be carried out. CCUS, as an advanced carbon capture and storage technology, not only helps achieve large-scale emission reduction but also promotes the complementary relationship between fossil energy and new energy.

Currently, multi-energy integration technologies in various fields in China are developing rapidly. However, research on marine integrated energy sustainability is still insufficient, and there are many problems to be solved. Therefore, it is urgent to leverage the diversified business advantages of large groups to promote internal industrial synergy and complementarity, and build a sustainable marine integrated energy base[2].

1.2 Research Objectives and Significance

The ocean holds vast energy resources and holds great potential for sustainable development. CCUS technology is crucial for achieving low-carbon or even zero-carbon transitions across industries. It also requires marine integrated energy to provide support through energy conversion. [3]For example, offshore wind power can be used for hydrogen production via water electrolysis, combined with CCUS technology to produce blue hydrogen and reduce carbon emissions. Additionally, captured carbon dioxide can be used for enhanced oil recovery (EOR) on offshore platforms, increasing oil and gas production and achieving carbon recycling.

1.2.1 Research Objectives

This research aims to explore the diversity and richness of marine integrated energy. It also analyzes the conversion and utilization of different energy sources and their value in recycling. The goal is to achieve sustainable marine integrated energy development by integrating CCUS technology with it[4].

1.2.2 Research Significance

This research holds great significance. It provides theoretical guidance and technical support for various industries undergoing low-carbon transitions. It helps achieve sustainable development and low-carbon transformation, contributing to the development of a strong energy nation and Chinese modernization.

The research addresses multiple issues.[5] It examines the current development trends of CCUS technology and marine integrated energy. It also explores ways to overcome existing development bottlenecks. Furthermore, it highlights that the development model and scale of marine energy are key to integrating CCUS technology, with the core focus being on achieving sustainable marine integrated energy development through CCUS technology integration.

2. Status of CCUS Technology and Marine Integrated Energy Development

2.1 Status of CCUS Technology Development

2.1.1 International Status of CCUS Technology Development

Internationally, CCUS technology has an early start and a relatively large scale. Countries such as the United States, Norway, and Canada are at the forefront in the research and application of CCUS technology. The United States is a leader in CCUS technology, with multiple large-scale projects, such as the Decatur project in Illinois and the Petra Nova project in Texas. The government supports the development of CCUS through tax incentives (e.g., the 45Q tax credit). Canada's Boundary Dam project is the world's first large-scale CCUS project, and the Quest project in Alberta has also made significant progress, with the government promoting CCUS technology through carbon pricing and subsidy policies. Norway's Sleipner project is one of the earliest CCUS projects globally, supported by carbon taxes and subsidies. [6]The United Kingdom has set a net-zero emission target for 2050 and supports CCUS projects such as Net Zero Teesside and Hynet through the Industrial Decarbonization Challenge Fund. The Netherlands' Porthos project aims to store carbon dioxide on the seabed of the North Sea, with government support through subsidies and policies.

It is evident that the international community is vigorously promoting the development and innovation of CCUS technology, with strong government support enhancing its advanced nature and competitiveness. This drives the circular utilization of carbon emissions in the country, ultimately promoting the sustainable development of energy.

According to the Global Status of CCS 2023 report by the Global Carbon Capture and Storage Institute, the number of global CCS (including CCUS) projects has grown for six consecutive years. As of July 2023, the total number of commercial projects at various stages reached 392, with an annual total capture capacity of 361 million tons. Global projects span a wide range of industries and are increasingly characterized by cluster development. These projects provide valuable experience for the commercial application of CCUS technology and push forward the global carbon emission reduction targets[7].

2.1.2 Domestic Status of CCUS Technology Development

CCUS technology in China started relatively late, but rapid development in recent years has led to significant progress. From basic research to industrial demonstration, progress has been made in all technical aspects. According to the China Carbon Dioxide Capture, Utilization & Storage (CCUS) Annual Report (2023), since the announcement of the carbon neutrality target, the scale of operational and planned CCUS demonstration projects in China has gradually expanded, covering industries such as power generation, coal chemicals, petrochemicals, cement, and steel. In August 2022, the Qilu Petrochemical–Shengli Oilfield project was launched, marking China's first million-ton-level CCUS project. [8]In September 2024, the first phase of the largest CCUS demonstration project in China—Ningxia's 3-million-ton/year CCUS demonstration project—was successfully accepted, signaling the entry of China's CCUS industry into a mature commercial operation phase. However, there are still many shortcomings in terms of cost and economic benefits. Therefore, China has included CCUS technology development in the 14th Five-Year Plan and introduced multiple policies to support its research and demonstration. In addition, some local governments, such as those in Inner Mongolia and Shaanxi, have also issued policies to support the development of CCUS[9].

2.2 Status of Marine Integrated Energy Development

2.2.1 Domestic Status of Marine Integrated Energy Development

In 1980, Academician Wu Zhonghua elaborated on the concept of total energy systems based on combined heat, cooling, and power (CHCP) systems using natural gas as the primary energy source [10]. This concept signifies the mutual transformation and sustainable utilization of different forms of energy.[10] In the same year, Gao Jingde from Tsinghua University proposed the concept of "modern power systems," which highlighted the necessity and interconnection of the high integration of power systems and communication technologies [11]. In 1998, the "Energy Conservation Law of the People's Republic of China" was enacted, stating that "the state encourages the development of energy cascade utilization technologies and combined heat, power, and cooling technologies to improve the comprehensive utilization rate of energy" [12]. Against the backdrop of its national conditions and energy development status, China has formulated energy construction plans and goals that best fit its development characteristics [13]. In 2012, relevant government departments in China issued the "Implementation Details for Natural Gas Distributed Energy Demonstration Projects," which provided policy support to guide distributed energy projects using natural gas as the energy source, thereby achieving distributed energy utilization[14].

China has abundant oil and gas resources in its maritime areas, and the exploration and development of marine oil and gas have always been important directions for long-term, significant production increases. [15]Under the trend of low-carbon transition in the energy system, finding a balance between increasing reserves and production and reducing carbon emissions, and achieving green development of marine oil and gas, is of great significance [16]. China's coastal areas are rich in diverse wind energy resources [17], which provide a solid foundation for large-scale and even ultra-large-scale offshore wind power development [18]. China has become the world's largest offshore wind power market, with a cumulative installed capacity exceeding 30 GW in 2022, accounting for more than 50% of the global total capacity. Representative projects include the Yangjiang Offshore Wind Power Base in Guangdong and the Rudong Offshore Wind Power Project in Jiangsu. Chinese companies (e.g., Goldwind and Mingyang Smart Energy) have made breakthroughs in large-scale wind turbines and floating wind power technologies. Therefore, China can center on the concept of energy islands in integrated energy systems and radiate to establish offshore wind turbines to more efficiently utilize marine wind energy. In addition, during the macro-design of energy islands, a horizontal connection can be made to further explore more distant maritime areas, laying the foundation for the development of deep-sea wind power projects. On this basis, China is promoting multi-energy complementary projects combining offshore wind power, photovoltaics, and energy storage, such as the Shandong Peninsula South Offshore Wind Power and Energy Storage Integration Project and the Guangdong Offshore Wind Power and Marine Ranch Integration Project. Moreover, China continues to develop offshore oil and gas fields in the South China Sea and Bohai Sea, while exploring the application of CCUS technology in these fields. [19]Several CCUS pilot projects have been launched domestically, such as the CO2-enhanced oil recovery and storage project in the Beibu Gulf of the South China Sea. The vigorous development of CCUS technology has brought new technological innovations to energy development and utilization, providing new directions and progress for the sustainable development of marine integrated energy[20].

2.2.2 International Status of Marine Integrated Energy Development

Between 2000 and 2017, Germany introduced and repeatedly revised the Renewable Energy Sources Act to expand the development of renewable energy and promote auction mechanisms for it. This has steadily increased renewable energy capacity under the "expansion path" target, ensuring its feasibility and economic viability. The global energy transition towards low - carbon and carbon - free models is accelerating due to climate change. IEA data shows that by 2030, non - fossil energy will account for 23.8% of global primary energy consumption. Renewable energy (excluding hydropower) will play an increasingly important role in the future non - fossil energy mix and will be the largest source of electricity growth[21].

3. Sustainable Development Models of Marine Integrated Energy

The sustainable development of marine integrated energy mainly lies in the comprehensive utilization of energy. Through the construction of distributed energy, multi - energy complementary systems, energy islands, and hybrid energy systems, marine energy can be planned effectively to boost energy efficiency and unlock the potential of marine renewable energy. An integrated energy system (IES) is a unified energy production and sales system that coordinates energy generation, conversion, transmission, and distribution. Focused on power systems, IES leverages diverse energy conversion and storage devices to achieve coordination, optimization, and complementarity among various energy systems. It improves energy efficiency by utilizing the different energy conversion and transmission characteristics of various sources, enhancing energy utilization flexibility[22].

China's marine integrated energy sustainable development models mainly include distributed energy and hybrid energy.

3.1 Distributed Energy Utilization

Distributed energy resources are a user - based energy supply method aiming to maximize benefits for demand, resources, and the environment. [23]This system can be optimized according to user energy demands and resource distribution. In July 2016, China issued the Implementation Opinions on Promoting the Demonstration Projects of Multi - energy Complementary Integrated Optimization. It proposed two major multi - energy complementary project models: One focuses on energy - efficient utilization and improving energy efficiency by understanding end - user energy demands, leveraging the complementary mechanisms of different energy sources, and forming tri - generation systems, smart microgrids, or distributed renewable energy. The other model involves integrating various renewable resources into a complementary system with combined energy characteristics. From an energy - circulation perspective, multi - energy complementarity lies in the interaction between different energy properties. [24]Through network coupling, energy topology reconstruction, and using different conversion technologies or devices, this approach achieves coupling in energy conversion and transmission, addressing energy system source - load mismatches and optimizing energy allocation for more efficient and innovative energy utilization and storage[25].

3.2 Hybrid Energy Utilization

A hybrid energy system integrates solar energy with wind energy, diesel, and grid electricity to enhance power supply reliability. It can meet loads' electricity needs in rural areas, islands, and communication base stations. [26]Hybrid power generation reduces environmental pollution, cuts CO_2 emissions, and lowers generation costs. Current hybrid energy systems mainly include wind - solar hybrid power and wind - hydrogen coupled generation[27].

Wind - solar hybrid systems feature excellent development performance and high reliability, primarily using wind power with solar power as an auxiliary. Wind - hydrogen coupled generation systems consist of wind turbines, electrolyzers, hydrogen storage devices, fuel cells, and power grids. [28]When wind power exceeds load demand or grid capacity, the surplus electricity is used for water electrolysis to produce hydrogen, effectively utilizing excess electricity.

Figure 1. China's Demonstration Base for Sustainable Development of Marine Integrated Energy

4. Research on the Sustainable Development of Marine Integrated Energy Combined with CCUS Technology

4.1 Complementary Mode of Offshore Wind Power and CCUS Technology

CCUS technology involves four key stages: carbon capture, transport, utilization, and storage. Offshore wind power generation can efficiently support marine technologies and industries. The carbon dioxide generated in this process is captured, transported, utilized, or stored via CCUS technology, achieving CO_2 recycling or long - term storage and maximizing carbon emission reduction to realize the goal of zero carbon emissions[29].

The integration of offshore wind power and CCUS technology offers significant potential and advantages in several aspects[30]:

(1) Energy Supply. Offshore wind power can provide clean electricity for all CCUS stages, reducing its life - cycle carbon emissions.

(2) Resource Integration. Offshore wind farms can be combined with CCUS projects in offshore oil and gas fields, using existing infrastructure like pipelines and platforms to cut CCUS costs.

(3) Regional Coordination. Coastal industrial zones or offshore oil and gas platforms can achieve low - carbon transitions through offshore wind power and CCUS technology, forming a "wind power + CCUS" green industrial chain.

(4) Technological Innovation. The integration of offshore wind power and CCUS can drive new technology development, such as offshore CO_2 electro - fuel production and algae farming. For example, offshore wind power can drive CO_2 electrolysis to produce methanol or synthetic fuels, or CO_2 can be used in offshore algae farming to produce biofuels or high - value chemicals.

(5) Energy Security and Independence. The combination of offshore wind power and CCUS can reduce fossil energy dependence. Coastal countries or regions can achieve energy self - sufficiency through offshore wind power and CCUS technology,

lowering energy import reliance.

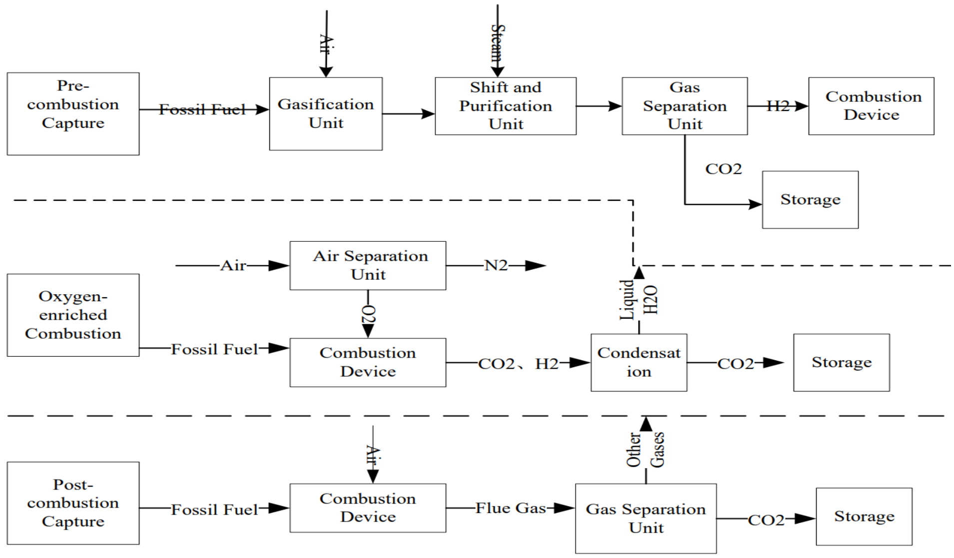

Figure 2. Carbon Dioxide Capture Methods

To achieve the integrated development of offshore wind power and CCUS technology, certain technical and conditional foundations are required. [30]When providing energy from offshore wind and electricity to marine - related industries, it's essential to install efficient carbon capture devices for prompt CO_2 collection during industrial operations. Next, the captured carbon emissions should be quickly transported or utilized using CCUS technology, with options like storing them in the ocean, thus forming a positive cycle of resource efficiency. Finally, it's crucial to continuously update and enhance CCUS technology to address its weaknesses and defects. This will make the technology more efficient in driving the development of various marine industries, ultimately establishing a complementary and integrated development model between offshore wind power and CCUS technology[31].

4.2 Integrated Development Mode of New Energy and CCUS Coupling

Firstly, make full use of the abundant wind energy resources along the coast. Plan and construct a total wind power generation capacity of 20 MW to 30 MW by engineering coupling wind power generation and utilizing green electricity. Configure the wind power scale according to 50% for self - use and 50% surplus for grid connection. Reduce the carbon increase during CO_2 capture to below 7%, achieving near - zero carbon - added green capture. [32]This will provide green electricity for the Guotou Beijiang Power Plant's million - ton - level CCUS integration demonstration project.

Secondly, adopt CO_2fracturing technology, which can increase crude oil production by 1.5 to 3 tons per ton of CO_2. Capturing enterprises and oilfield companies can collaborate in designated areas. Capturing enterprises handle carbon supply, transportation, and enhanced oil recovery operations, while oilfield companies provide blocks, wellheads, and subsequent production facilities. The revenue from the block's crude oil production is shared proportionally. This approach realizes the resourceful and efficient use of CO_2, promoting the sustainable development of marine energy.

The integration of new energy (such as wind and solar power) with CCUS technology is a crucial way to achieve carbon neutrality.[33] This coupling model not only maximizes the advantages of clean energy and carbon management but also creates multiple benefits in energy system transformation. The main advantages are as follows[34]:

(1) Deep Decarbonization. New energy supplies clean electricity to CCUS, reducing carbon emissions during carbon capture, transport, and storage. This achieves full - lifecycle deep decarbonization. Wind or solar power for carbon capture equipment avoids fossil - energy electricity, lowering CCUS's carbon footprint. The two technologies work together to maximize energy utilization.

(2) Reduced CCUS Costs. New energy costs are decreasing yearly, and resources are plentiful. This provides CCUS with low - cost, stable electricity, cutting operational costs. In regions rich in wind or solar resources, integrated new energy and CCUS projects reduce grid - electricity reliance and lower power costs.

(3) Enhanced Energy Efficiency. New energy and CCUS integration optimizes energy efficiency. For instance, surplus renewable electricity can power carbon capture equipment, or CCUS can handle fossil - energy carbon emissions when new energy generation is insufficient. During peak wind or solar generation, surplus power is used for carbon capture; during low generation, CCUS manages traditional energy carbon emissions.

(4) Low - Carbon Transition for High - Emission Industries. The integration offers feasible low - carbon solutions for industries like steel, cement, and chemicals, aiding deep emission reductions. For example, building new energy generation facilities in industrial parks with CCUS technology provides clean electricity and carbon management services for park enterprises.

(5) Support for Carbon - Neutrality Goals. The integration significantly cuts CO_2 emissions, offering key support for national and regional carbon - neutrality targets. Large - scale integrated projects in new - energy - rich areas achieve dual goals of clean energy production and carbon management.

(6) Resource Integration and Synergistic Development. The integration enables efficient resource use and infrastructure sharing, lowering project investment and operational costs. Power from new energy generation facilities can drive carbon capture equipment, or existing CO_2 transport and storage infrastructure can serve multiple projects.

4.3 Integrated Development Mode of Marine Integrated Energy

Generate electricity through offshore wind power, tidal energy, salinity gradient, and photovoltaics to supply power for the offshore "energy island" and daily life.

After crude oil is extracted by offshore drilling platforms, it is transported via subsea pipelines to the chemical plant on the "energy island" for refining and cracking. The resulting fuel oil and natural gas are stored in underground storage reservoirs and hydrogen storage facilities under the sea. In severe climates, thermal power generation can supply electricity to the "energy island". Surplus electricity from offshore wind power and photovoltaics can be used for electrolyzing seawater to produce hydrogen and ammonia. Mixing hydrogen and ammonia in certain proportions can greatly increase fuel calorific value and improve energy efficiency. CO_2 from chemical plants, electrolysis exhaust, and daily life on the "energy island" can be stored using CCUS technology. Oxygen, a by - product of seawater electrolysis for hydrogen and ammonia production, can supply oxygen for offshore ranches and deep - sea mineral exploitation, and can be used with collected CO_2 for microalgae cultivation to provide provisions for passing vessels and fleets[35].

Marine integrated energy integrated development refers to the combination of various energy technologies (such as offshore wind power, marine energy, hydrogen energy, CCUS, etc.) with energy storage, transmission and utilization systems, to form an efficient and collaborative energy ecosystem. This development model has significant advantages and can strongly support energy transition and sustainable development. The main advantages of marine integrated energy integrated development are as follows[36]:

(1) Enhanced Energy Efficiency. Through the collaborative operation of multiple energy technologies, such as complementary power generation from offshore wind power and marine energy (e.g., wave and tidal energy), and using hydrogen energy to store surplus electricity, energy utilization efficiency can be improved.

(2) Improved Energy System Stability. The combination of multiple energy technologies can balance the volatility of energy supply and enhance the stability of the energy system. When offshore wind power generation is insufficient, marine energy or energy storage systems can supplement power supply. When power generation is excessive, surplus electricity can be used for hydrogen production or carbon capture.

(3) Accelerated Energy Structure Transformation. Marine integrated energy integrated development can accelerate the large - scale application of renewable energy, reduce dependence on fossil energy, and promote the clean and low - carbon transformation of the energy structure. For instance, offshore wind farms can be built near offshore oil and gas platforms to supply power to the platforms, with CCUS technology handling carbon emissions from oil and gas production.

(4) Promoted Regional Coordinated Development. Marine integrated energy integrated development can boost the economic growth of coastal areas and promote regional coordination and sustainable development. Building marine integrated energy bases in coastal areas can provide clean energy for local industries, transportation, and residents, while creating job opportunities.

(5)Fostered Technological Innovation. Marine integrated energy integrated development requires collaborative innovation of multiple technologies, driving progress and breakthroughs in energy technologies. This involves developing technologies such as offshore wind power - hydrogen energy coupling, marine energy power generation and energy storage, etc., to promote the diversified development of energy technologies.

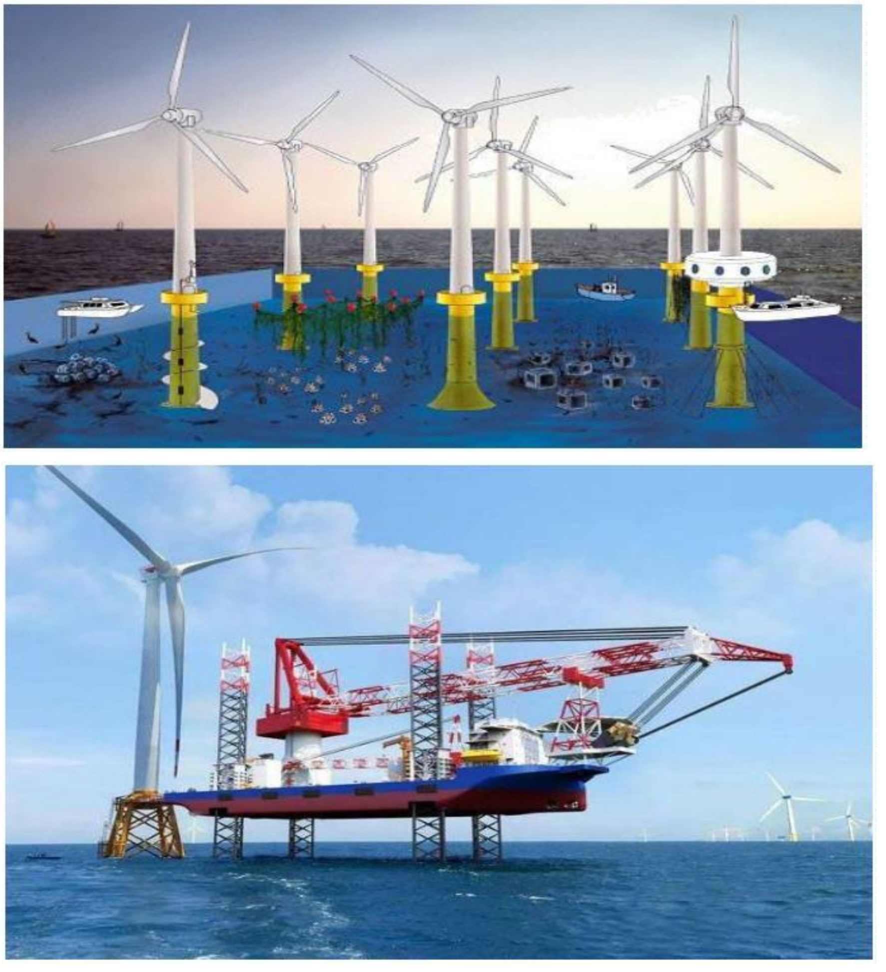

Figure 3. Integrated Development Model of Marine Integrated Energy

5. Challenges of CCUS Technology under the "Dual Carbon" Context

5.1 Technical Maturity and Cost

Although CCUS technology has made progress globally, its maturity still needs to be improved. The high costs of key technologies in carbon capture, transport, and storage remain a major challenge. The high capture costs, mainly from chemical reagents and energy consumption, are significant, especially in the limited space and energy conditions of ships. Additionally, the infrastructure construction costs for ship - based CCUS technology, such as storage and transport facilities, increase the total project investment. The energy consumption of the capture process is also substantial, as capturing CO_2 requires significant energy, often from fossil fuels, leading to extra carbon emissions.

5.2 Regulations, Policies, and Incentive Mechanisms

The promotion of CCUS technology requires robust regulations and incentive mechanisms. China has introduced some policies to support CCUS development, but a comprehensive policy system is still lacking. Further improvements are needed in areas like carbon trading market development, tax incentives, and financial subsidies[37].

5.3 Social Awareness and Acceptance

As an emerging technology, CCUS has low social awareness and acceptance. Limited public understanding and concerns over its safety and environmental impact pose challenges. Enhancing public awareness and acceptance through science popularization is crucial for CCUS technology promotion[38].

6. Conclusions and Future Outlook

6.1 Conclusions

In the context of China's "dual carbon" goals, developing and applying CCUS technology is vital for global carbon reduction. The mutual coordination between CCUS technology and marine integrated energy has two main aspects. On one hand, CCUS can reduce carbon emissions from marine oil and gas extraction and offset emissions from offshore wind power production and maintenance. On the other hand, the integration of various marine energies can optimize carbon management and improve overall efficiency. Offshore wind power can supply clean electricity for CCUS facilities, reducing carbon capture costs and enhancing CCUS economic benefits.

Future development trends of CCUS and marine integrated energy are as follows. In terms of policy, the Chinese government will increase support for CCUS technology, improve regulations to boost R&D and application, and make CCUS a key corporate tool for carbon emission reduction and green transition as the national carbon market develops. In terms of technology, China will achieve substantial progress in CCUS R&D through introducing foreign technology and domestic innovation, reducing costs and improving promotion efficiency. In terms of the market, the CCUS industrial chain will become more complete with technology maturation, forming a full - fledged chain from CO_2 capture to utilization and storage, and giving rise to new industry forms and business models to drive socio - economic development. Ultimately, industries like power, steel, and cement will transition to standardized CCUS application models from desulfurization and denitrification.

China's CCUS technology has a broad development prospect. Its industrialization will promote high - quality low - carbon economic growth. With the joint efforts of policies, technology, and the market, CCUS is expected to play a more important role in carbon reduction, energy transition, and environmental protection, making a greater contribution to global climate change mitigation.

6.2 Future Outlook

Marine integrated energy integration is crucial for sustainable development and energy security. To address challenges like weakened investor willingness, excess backward production capacity, and relatively single industrial financing channels, China has adopted several policy measures to boost the marine economy. The future outlook for promoting sustainable marine energy development is as follows[38]:

(1) Optimize Supporting Policies. In line with the "dual carbon" goals, coordinate marine energy sites, plan marine energy layout, integrate oil and gas resources, and improve the integrated energy industry chain. Implement supporting policies, refine marine planning, optimize the configuration around oil and gas platforms, simplify approval processes, and enhance development efficiency. Combine national policy guidance with market mechanisms to promote marine energy transmission and consumption, ensuring the economic and reliable coordination of marine energy scheduling and improving its scale benefits.

(2) Promote Technological Innovation. Increase research investment, cultivate professionals, and coordinate resources to drive innovation in marine integrated energy technologies like offshore wind power, tidal energy, and ocean thermal energy. Advance the domestic development of key core technologies. Enhance national support for modern technologies such as marine energy digitalization and informatization. Promote research in offshore power generation, energy storage, and oil and gas technologies. Improve the technical level and economic benefits of offshore equipment manufacturing and construction maintenance to boost the overall technological and economic performance of marine integrated energy.

(3) Strengthen Industrial Synergy. Coordinate the upstream and downstream of the industrial chain, integrate entities to adapt to different marine regions, and establish a marine integrated energy industry chain. Promote the coordinated development of energy industries such as wind power, solar energy, and ocean thermal energy. Integrate offshore wind power with hydrogen energy, zero - carbon oil extraction, hydrogen storage, and electricity storage to develop a diversified marine energy supply system.

(4) Enhance International Cooperation. Share technologies and experiences with international partners to promote international cooperation in marine integrated energy and achieve resource sharing. Learn from advanced foreign marine experience through "bringing in" and "going global" strategies, and develop technologies suitable for China's marine conditions, resources, and climate. Participate more in international industry standard - setting through joint training.

(5) Improve Energy Efficiency. Introduce advanced wind power technologies and

equipment to fully utilize marine resources. Scientifically select locations and optimize wind power layouts to maximize wind energy efficiency and reduce transmission losses. Combine ocean thermal energy with seawater desalination technology for integrated energy and freshwater production. Strengthen energy management, promote energy - saving technologies, and reduce energy consumption and CO_2 emissions to improve energy efficiency.

(6) Achieve System Synergy and Enter the Carbon - Neutral Era. Use 时空 analysis and intelligent decision - making to precisely match carbon emission sources with CCUS technologies, maximizing emission reduction potential. Optimize CCUS technology layout to enhance CO_2 capture and storage efficiency, promote large - scale marine and renewable energy development, drive negative emission technology innovation, and achieve positive interaction and coordinated development among energy, resources, and the environment.

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